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# HYPERSPECTRAL ATMOSPHERIC COMPENSATION THROUGH CLOUDS AND AEROSOLS WITH PHYSICS-BASED RADIATIVE TRANSFER ALGORITHMS

January 1998

Thomas R. Caudill, Gail P. Anderson, Laila S. Jeong
Air Force Research Laboratory
29 Randolph Road
Hanscom AFB, MA 01731-3010

Robert P. d'Entremont, Gary B. Gustafson
Atmospheric and Environmental Research
840 Memorial Drive
Cambridge, MA 02139

Alexander Berk, Larry S. Bernstein
Spectral Sciences, Inc.
99 S. Bedford Street
Burlington, MA 01803

## ABSTRACT

Current concepts for the employment of Hyperspectral Imagers (HSI) for surveillance assume nearly ideal atmospheric viewing conditions. In reality clouds and aerosols will be important considerations for military operations. In the presence of optically thick clouds, visible and IR measurements provide virtually no information about what is occurring below the clouds. However, the situation is different for thin cirrus clouds and tenuous aerosol plumes, where energy from the surface is transmitted through the obscurant to the observing platform. Being able to operate with atmospheric opacities of 1 (~30% additional extinction due to thin clouds or aerosols) with appropriate S/N ratios will increase the effective operational capabilities dramatically. This will be especially important for satellites and UAV's operating over tactical domains. The Air Force Research Laboratory has recently developed new multispectral cloud and aerosol analysis techniques which, along with algorithms to maximize the atmospheric signatures, make it possible to sufficiently characterize the optical properties of transmissive cirrus and assorted aerosols. In conjunction with evolving atmospheric compensation tools, these techniques will potentially allow increased analysis of hyperspectral surveillance data in the presence of realistic contamination. Recent and proposed enhancements to the SERCAA and MODTRAN algorithms can be used to quantify the effect of clouds/aerosols on system performance. In particular, new algorithms to retrieve radiative, microphysical, and optical properties are being exploited to more fully characterize the required inputs for the radiative transfer codes including FLAASH, a developing atmospheric compensation algorithm. Additionally, spatial extent of such obscurants can be exploited using cross-pixel analyses. While 'anomaly detection' can often be accomplished without resorting to atmospheric compensation, 'production and delivery of on-time, assured, and actionable intelligence products to the user' will require identification of surface and effluents in any surveillance mode. Only 'complete' accommodation for the natural atmospheric variability will provide the essential corrections to achieve the necessary level of accuracy required by the surveillance community.

# REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188



1. REPORT DATE (DD-MM-YYYY)
01-01-1998

2. REPORT TYPE
Conference Proceedings

3. DATES COVERED (FROM - TO)
xx-xx-1998 to xx-xx-1998

4. TITLE AND SUBTITLE
Hyperspectral Atmospheric Compensation Through Clouds and Aerosols with Physics-Based Radiative Transfer Algorithms
Unclassified

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Caudill, Thomas R. ;
Anderson, Gail P. ;
Jeong, Laila S. ;
d'Entremont, Robert P. ;
Gustafson, Gary B. ;

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME AND ADDRESS
Air Force Research Laboratory
29 Randolph Road
Hanscom AFB, MA01731-3010

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME AND ADDRESS
Director, CECOM RDEC
Night Vision and Electronic Sensors Directorate, Security Team
10221 Burbeck Road
Ft. Belvoir, VA22060-5806

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
APUBLIC RELEASE
,

13. SUPPLEMENTARY NOTES
See Also ADM201041, 1998 IRIS Proceedings on CD-ROM.

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:

| a. REPORT | b. ABSTRACT | c. THIS PAGE |
|---|---|---|
| Unclassified | Unclassified | Unclassified |

17. LIMITATION OF ABSTRACT
Public Release

18. NUMBER OF PAGES
9

19. NAME OF RESPONSIBLE PERSON
Fenster, Lynn
lfenster@dtic.mil

19b. TELEPHONE NUMBER
International Area Code
Area Code Telephone Number
703767-9007
DSN
427-9007

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39.18

## 1.0 INTRODUCTION

Clouds and aerosols represent a significant uncertainty in the effectiveness of a large number of Air Force satellite and aircraft systems including Hyperspectral imagers. Hyperspectral imager data requires that the atmospheric component, whether signal or contaminant, be identified and 'corrected' as quickly as possible for the whole image. Any delay in rectifying images to their highest quality will impact the use of the spectral image as a surveillance resource tool. Identification of surface properties is the productive 'end service' of these class of instruments, whether they are space, aircraft, UAV, or surface technologies. Therefore, the risk factors are: (1) time minimization of the compensation product; (2) degree of extension into adverse weather conditions which will still be productive to the user community; (3) accurate separation of components which contribute to the total signature; (4) maximization of data fusion products and whether those resources can be sufficiently co-located.

The goal of this effort is a self-sufficient 'atmospheric compensation algorithm' with compatible interfacing capabilities with existing and/or proposed hyperspectral sensors. This system will emphasize the optimization of information content related to all atmospheric constituents over the available spectral ranges. Output will include an assessment of all errors introduced by the system, including cloud/aerosol contaminants and molecular/temperature profiles (including surface temperatures). This error analysis will be ongoing from the onset of the program, as the various components begin to be merged. These errors cannot exceed the requirements of the surveillance community.

We will describe our ongoing research into developing a physical retrieval algorithm designed to exploit the full range of hyperspectral data to improve accuracy and content of cloud-, aerosol-, surface-, and atmospheric-property characterization. The algorithm involves iteratively solving a physically-based forward radiance model. In the visible and near-IR spectral ranges, such retrievals will include terrain mapping (with available $O_2$ or $CO_2$ lines), $H_2O$ column abundances (differentiated from clouds and surface water), plus additional non-linear contributions. At other wavelengths (e.g. ozone in the UV, $H_2O$ in the IR), more specific information about vertical distributions may be available; future surveillance systems can be expected to include these broader spectral domains.

Because of prior work in cloud algorithms, radiative transfer codes, and atmospheric characterization (including aerosols), some of this effort involves filling gaps in existing technologies or joint applications of technologies not currently merged. In addition, there is a new capability centered on FLAASH (Fast LOS Atmospheric Analysis of Spectral Hypercubes) which is just entering the development stage. While other atmospheric algorithms are available, the extension of the compensation techniques to thin clouds and aerosols, plus the retrieval capability based on the new MODTRAN4 implementation will provide an extraordinary new tool that will include spatial information.

This effort meets critical technology needs for imagery exploitation and enhanced data fusion by taking advantage of the large number of wavelengths and pixels available from a hyperspectral instrument. This permits compensation for multiple forms of atmospheric contamination or signature enhancement, allowing successful operation of air- and space-borne surveillance technologies under adverse conditions. Current capabilities are almost entirely limited to 'clear-sky', so being able to operate with atmospheric opacities of 1 (~30% additional extinction due to thin clouds or aerosols) with appropriate S/N ratios will increase the effective operational capabilities dramatically. This will be especially important for satellites and UAV's operating over tactical domains.

## 2.0 CLOUD PROPERTY RETRIEVAL

AFRL Battlespace Environments Division (AFRL/VSB) in collaboration with Atmospheric and Environmental Research, Inc. (AER) has been actively involved in research for cloud property retrieval from various satellite platforms under sponsorship of the National Technical Means (NTM) MEDEA and the Space Based Infrared System (SBIRS) programs. Research in the area of satellite-based cloud detection and characterization has included numerous enhancements to the operational RTNEPH cloud model run at the

Air Force Weather Agency (AFWA, formerly AFGWC), development of a tactical cloud analysis capability that could be put on the Small Tactical Terminal, and culminating in development of a comprehensive set of algorithms for analysis of data from all available polar and geostationary environmental satellites, both military and civilian.

The principal tool in these investigations is a suite of cloud analysis algorithms developed under a program known as Support of Environmental Requirements for Cloud Analysis and Archive (SERCAA) (Gustafson et al., 1994 and 1996). SERCAA development was funded by DoD, DoE and EPA under the Strategic Environmental Research and Development Program (SERDP). The SERCAA algorithms have been selected for operational implementation at AFWA to replace the aging RTNEPH technology as part of the current Cloud Depiction and Forecasting System II (CDFS II) upgrade.

Recent enhancements to the SERCAA algorithms have been used by the SBIRS Phenomenology Exploitation Program to help quantify the effect of clouds on system performance. These effects are primarily due to high altitude cirrus cloud structure when viewing the Earth from space. The characteristics of optically-thin cirrus are poorly understood but have significant impact on satellite and aircraft sensors and weapons. The objective of the cirrus cloud detection and modeling effort is to improve our understanding of the properties and conditions for cirrus clouds, particularly optically thin cirrus. In particular, new algorithms to retrieve cirrus radiative, microphysical, and optical properties are being exploited to more fully characterize the cloud background, to initialize cloud simulation algorithms, and for intercomparison with other retrieval approaches including ground-based lidar and radar measurements.

Current requirements focus on the need for improved characterization of cloud optical properties to support modeling and simulation of cloud impacts on radiative transfer through the atmosphere. The principle emphasis has been on specification of transmissive cirrus properties from satellite data (Ou et al., 1993a, 1993b, 1997a and 1997b; Rao et al., 1995; d'Entremont et al., 1996). The transmissive nature of cirrus clouds turns out to be its most important and elusive (in a retrieval sense) attribute to specify. If the semi-transparent nature of cirrus clouds is not accounted for, the cloud altitude is consistently underestimated when using passive infrared brightness temperature data. For example, in the case of very thin (sub-visual) cirrus, ice particles have a more significant interaction effect with incident solar and upwelling thermal radiation than does upper tropospheric water vapor (Smith et al., 1990).

A major limitation to the cirrus retrieval work accomplished under SERCAA and continuing under current programs, has been the lack of ground truth data suitable for algorithm validation. A need exists for comprehensive sets of data and models regarding the impacts of cirrus clouds on hyperspectral imagers. Cloud property information (size distribution, particle shape, etc.) of thin and sub-visible cirrus also requires additional investigation. Databases such as FIRE, FIRE-II, and SUCCESS need further analysis to determine what information can be extracted from them. There is also the new cirrus cloud database collected by the SBIRS program which will be discussed below.

## 3.0 MODTRAN UPGRADES AND FLAASH

MODTRAN3 is already integrated into the NASA AVIRIS analysis, but MODTRAN4 will potentially be able to extend in both the spatial and spectral analysis domains because of the newly formulated Beer's Law capability which allows accurate separation of the down-welling and up-welling transmittances, only approximated within other algorithms. This, along with more accurate cloud and aerosol description, will facilitate examining images not only in a pixel mode, but also with adjacency enhancements that can extend to larger portions of the total image.

Development of MODTRAN4 was necessary because MODTRAN3 predictions of multiply scattered solar radiances in spectral regions with non-continuum molecular absorption may be inaccurate. This scenario cannot be validated by comparisons to FASCODE (Clough et al., 1988) because it lacks a solar capability. Thus, initial validation of MODTRAN4 multiply scattered solar calculations were made directly to measurements (see Anderson et al, 1997).

The new MODTRAN4 band model (Bernstein, et al., 1996b), with its correlated-k algorithm, can efficiently and correctly (usually within 3-5%) calculate the scattering and absorption signatures of realistic molecular, aerosol and cloudy environments in the lower and middle atmosphere. The current approach for molecular scattering accommodates line overlap and partial correlations between both molecular species and the solar irradiance, while maintaining band model spectral resolution at 2 or 15 $cm^{-1}$. While this version of MODTRAN is grounded in the prior series of AF radiative transfer band model (BM) algorithms (Kneizys, et al., 1980, 1983, 1988, Berk et al., 1989), it is distinct in its ability to employ Beer's law to describe local layer, species-specific transmittance for input to the radiance calculations. While this capability is not always necessary, it allows appropriate handling of multiple scattering using existing non-BM algorithms (DISORT, Stamnes et al., 1988, and Isaacs et al., 1987). MODTRAN4, while maintaining the basic 2 $cm^{-1}$ spectral resolution, can now complement the multiple scatter routines by introducing a Correlated-*k* (CK) capability which is expressly compatible with Beer's law formulations. MODTRAN4 also provides greatly improved predictive capabilities under cloudy and/or heavy aerosol loading conditions in both the visible and IR by allowing the explicit definition of water and ice cloud vertical profiles and spectral data, either by scaling and combining default model clouds or by redefining entirely new model clouds with micro-layering options.

Addition of a CK capability to MODTRAN (Bernstein et al., 1996a) provides an accurate and fast means for evaluation of the effects of clouds and heavy aerosol loading on retrievals (both surface properties and species concentration profiles) and on atmospheric radiative heating/cooling calculations. These radiative transfer computations require coupling the effects of gaseous molecular absorption due primarily to water vapor, carbon dioxide, and ozone, with particulate multiple scattering due to volcanic aerosols, ice crystals, and water droplets. In order to adapt a band model approach for use in scattering calculations it is necessary to express the band model transmission function in terms of a weighted sum of Beer's law exponential terms. Thus, a method for determining the weighing factors and monochromatic absorption coefficients for the MODTRAN band model is required. For a more complete discussion of the CK method the reader is referred to Lacis and Oinas (1991).

It can be shown that this combination of improvements will permit rapid identification of atmospheric contaminants/signatures in window regions while in the regions of molecular opacity, where weighting functions peak in the atmosphere, it is expected that MODTRAN4 can play a role in very quick retrievals. This can be accomplished by avoiding the large number of line-by-line (LBL) calculations necessary for initiating derivative (perturbation) matrices (Anderson et al., 1993). While the error estimates and residuals associated with a 2 $cm^{-1}$ algorithm will be larger than those associated with LBL retrievals, the speed advantage for image processing warrants this initial approach.

FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes) is a MODTRAN-based "atmospheric correction" software package which is being developed by the AFRL/VSB and Spectral Sciences, Inc. to support current and planned IR-visible-UV hyperspectral and multispectral sensors. The main objectives are to provide (1) accurate, physics-based derivation of surface and atmospheric properties (such as surface albedo, surface altitude, water vapor column, aerosol and cloud optical depths, surface and atmospheric temperatures), (2) minimal computation time requirements, and (3) an interactive, user-friendly interface for running arbitrary MODTRAN calculations. FLAASH is written in the Interactive Data Language (IDL) (Research Systems, Inc., Boulder, CO) for compatibility with a wide variety of computer platforms and to facilitate its use with IDL-based display/analysis software such as ENVI.

FLAASH draws heavily on existing spectral analysis methods and codes that have been developed for both research and general use (e.g., Gao et al., 1996; Green et al., 1996; King et al., 1992; Richter, 1996; Wan and Li, 1997). It is designed as a general-purpose code and is being developed in parallel with upgrades to MODTRAN in order to take advantage of the latest improvements in accuracy and speed. FLAASH is currently interfaced with a pre-release version of MODTRAN4. The initial version of FLAASH provides the following capabilities:

- Support for AVIRIS, HYDICE, and similar near-IR/visible/UV sensors;
- A graphical user interface for performing MODTRAN4 spectral calculations, including data simulations;

- Data-derived column water vapor and relative surface altitude (from column oxygen) image files and displays, and aerosol property retrieval capability based on known surface reflectances;
- Atmospherically corrected images (i.e., surface spectral reflectances) for non-thermal wavelengths (mid-IR through UV), including an image-sharpening adjacency effect correction.

The algorithm for deriving the surface and atmospheric properties utilizes the full MODTRAN4 accuracy and accounts for adjacency effects associated with atmospheric scattering. Compared to previous versions of MODTRAN, the new correlated-k radiation transport algorithm in MODTRAN4 (Berk *et al*., 1996) provides improved accuracy in treating molecular absorption over scattering paths. In addition, an order of magnitude reduction in computation time is achieved by using MODTRAN4's lower resolution (15 $cm^{-1}$) option.

As in other first-principles atmospheric correction codes, model simulations of the spectral radiance are performed for appropriate atmospheric and viewing conditions over a range of surface reflectances. The desired properties (reflectance, column water vapor, etc.) are derived from the spectral radiance at each image pixel using look-up tables that are generated from these simulations. To minimize the number of simulations (i.e., MODTRAN runs) required to generate the tables, a physics-based parameterization of the radiance-reflectance relationship is used. This relationship can vary across the scene due to variations in water vapor column density. Therefore, as in the ATREM code (Gao *et al.*, 1996) the water vapor column is first determined for each pixel, then the result is used as an input to the surface reflectance retrieval algorithm.

The computation time consumed for a typical analysis of an 0.4-2.5 µm hyperspectral image on a 200-MHz personal computer is five to fifteen minutes for the MODTRAN4 calculations (depending on the number of water vapor column amounts and atmospheric layers and on the code options used) plus ten to fifteen minutes for the data inversion (water column determination, spatial averaging, and generation of surface reflectance) for an AVIRIS 224-channel, 512x614-pixel image. Since the MODTRAN4 outputs are stored, they can be re-used to analyze a series of images taken under similar atmospheric conditions.

In addition to determining the water vapor column density, FLAASH derives pressure altitudes by applying the same method to the oxygen 762 nm absorption band. Because MODTRAN4's correlated-k algorithm more accurately represents molecular absorption in the presence of scattering, the water vapor and oxygen densities derived from FLAASH are expected to be more accurate than those obtained using previous versions of MODTRAN as well as from more approximate radiation transfer algorithms.

Development of FLAASH has begun with a focus on sensors covering near-IR through UV wavelengths. An initial version of the code has been developed for analysis of AVIRIS and HYDICE data. Ongoing efforts will focus on accuracy evaluations, improvements to MODTRAN4, incorporation of a comprehensive library of reflectance spectra, incorporation of aerosol and cloud retrieval techniques, and extensions of FLAASH to additional sensors and to the thermal IR region.

## 4.0 FUTURE DEVELOPMENT WORK

Pieces of the program are in place for clear-sky as demonstrated particularly by AVIRIS, HYDICE (Vis/NIR) and SEBASS (IR) but the extension to heavier obscuration, through the merging of new cloud and aerosol optical retrievals, emerging non-linear inversion algorithms and data fusion, requires additional research. Work by Snow et al. (1997) has shown that it is possible to compensate for the presence of thin cirrus clouds in the GOES 3.9 µm channel using Numerical Weather Prediction (NWP) products to specify the atmospheric parameters for MODTRAN. A local retrieval of the desired parameters should improve the compensation procedure.

We are currently analyzing HYDICE measurements of scenes containing spectrally calibrated targets. Comparisons of retrieved and known surface reflectances will be very useful for inferring aerosol properties, which are the major source of uncertainty in visible and UV surface reflectance retrievals for clear-sky conditions. Either calibrated targets or "dark" pixels (known to contain vegetation or water) can be compared with retrieved reflectances as an aerosol optical property is varied, the property being retrieved

from the best fit. Ultimately the non-linearities will require employing a 'unified retrieval' algorithm, pulling appropriate signature data from all contributing portions of the spectrum (and/or neighboring pixel spectra), an approach now under development within AFRL. Aerosol properties which may be potentially retrieved (i.e., to which the comparisons are sensitive) include the optical depth, albedo, and scattering phase function (via the adjacency effect).

As mentioned earlier the SBIRS Phenomenology Exploitation Program carried out a number of data collections using satellites, aircraft, lidars, radars, and other instruments. Some instruments collected IR data while other collected "ground truth" information about the cloud environment to provide a more complete description of the scene. The primary IR instrument that is being applied to this work is the ARES aircraft which collected data with its 2.0 - 6.4 μm, 75-channel imaging spectrometer. Ground truth providers included the Aeromet HARP aircraft which collected radar, lidar and particle probe data in and around the clouds. The University of Wisconsin High Spectral Resolution Lidar (HSRL) and Volume Imaging Lidar (VIL) provided high resolution information about the cloud structure for thin clouds (up to optical depth 4) (Wylie et al., 1995; Piironen and Eloranta, 1995), while the University of Massachusetts' Cloud Profiling Radar System (CPRS) (Firda et al., 1996) and the AFRL/VSB TPQ-11 radars provided data when optically thick low clouds obscured the lidars. Radiosonde data was also collected for most of the coordinated operations. In addition to the imagery collected from the GOES and NOAA weather satellites, a number of analysis products were also generated including cloud analyses using the SERCAA algorithm.

Portions of this data collected over Hanscom AFB, MA and Madison, WI in September 1995 and over Everglades City, FL in September 1996 are being analyzed to determine cirrus cloud temperature and composition using ARES data. This method uses the 5.1 - 5.3 μm channel radiances to compute cirrus cloud temperatures and IR emissivities. The ice crystal mean effective size is determined by matching the 3.755 μm ARES channel with the modeled 3.7 μm reflected solar and IR emitted radiance. Retrieval results show good agreement with coincident HARP aircraft and ground-based radar measurements. We intend to explore the utility of other bands to provide additional information in the retrieval process. Benefits include extremely accurate retrieval of cloud top pressure, detection of very thin cirrus, and improved accuracy for cloud particle size, phase and ice content. Work by Burke et al. (1998) on the retrieval of water vapor profile information from ARES data is presented elsewhere in this volume.

We are also exploring the utility of the MODIS Airborne Simulator (MAS) data and algorithms for developing hyperspectral retrieval techniques (King et al., 1996). MAS is a 50-channel imaging spectrometer which is flown on NASA's high-altitude ER-2 research aircraft. Although MAS is a multispectral instrument, it covers the spectral range from 0.55 to 14.2 μm. This data will serve as the bridge between the Vis/NIR data from AVIRIS and HYDICE to the LWIR data collected by SEBASS.

## 5.0 CONCLUSIONS

AFRL scientists have been actively supporting Air Force requirements in the area of satellite-based cloud detection, radiative transfer codes suitable for hyperspectral applications, and atmospheric characterization (retrieval algorithms). Building upon existing expertise in the field of multispectral atmospheric analyses (molecular, cloud, and aerosol), we are developing algorithms to characterize quasi-transparent obscurant properties using hyperspectral imagery. This capability will allow more accurate compensation for atmospheric and meteorological phenomena to support improved target detection and surveillance over a wider range of conditions.

This effort will aid evolutionary and ongoing research into a physical retrieval algorithm designed to exploit the full range of hyperspectral data to improve accuracy and content of cloud-, aerosol-, surface-, and atmospheric-property characterization. The expected benefit is a significant enhancement to performance over currently problematic conditions through the addition of needed information content, particularly in the visible and near to mid-wave IR portions of the spectrum, but also inclusive of the IR. Information maximization and data fusion (using mm-wave and UV technologies, as available) will provide complementary resources.

This effort meets some of the technology needs for imagery exploitation and enhanced data fusion by taking advantage of the large number of wavelengths available on a hyperspectral instrument to compensate for transmissive clouds. By removing the effects of thin clouds the algorithms will produce a more accurate spectral signature which will make automatic target detection and recognition under a wider variety of conditions possible. By improving the atmospheric compensation a larger number of camouflaged targets may be identified and it will allow for more accurate Battlefield Damage Assessment (BDA).

While 'anomaly detection' can often be accomplished without resorting to atmospheric compensation, 'production and delivery of on-time, assured, and actionable intelligence products to the user' will require identification of surface and effluents in any surveillance mode. Only 'complete' accommodation for the natural atmospheric variability will provide the essential corrections to achieve the necessary level of accuracy required by the surveillance community.

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